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Dry Ball Milling with Pneumatic Classification in Mineral Comminution Systems: Fundamentals, Circuit Integration, Energy Efficiency, Industrial Performance, and Technology Selection—A Critical Review

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Abstract

Dry comminution may be advantageous where freshwater constraints, dewatering requirements, or flowsheet integration complicate slurry circuits. This structured narrative critical review evaluates dry ball milling coupled with pneumatic classification, distinguishing air-swept operation from mechanically discharged mills with external classification. Its documentary basis is a supplied bibliography described as containing 148 candidate records; a reproducible search history and a complete full-text appraisal log were not available. Sources are interpreted as direct circuit evidence, component-level evidence, methodological support, or comparisons with other routes, with study scale considered separately. Mill power alone does not establish circuit performance: classifier selectivity, recycle, pneumatic pressure losses, dust collection, moisture, and downstream liberation must be evaluated together. Published component studies support the relevance of these mechanisms, but the supplied record does not permit a literature-wide estimate of independently audited integrated mineral-ore plants. The proposed appraisal framework specifies measured dry-solid balances, partition curves, equipment-level electrical demand, separately reported thermal duty, product quality, and common-boundary economic assessment. Conclusions are conditional on ore-specific testing rather than claims of universally superior industrial performance.

Keywords: Dry ball milling; Pneumatic classification; Mineral comminution; Energy efficiency; Closed-circuit grinding; Technology selection

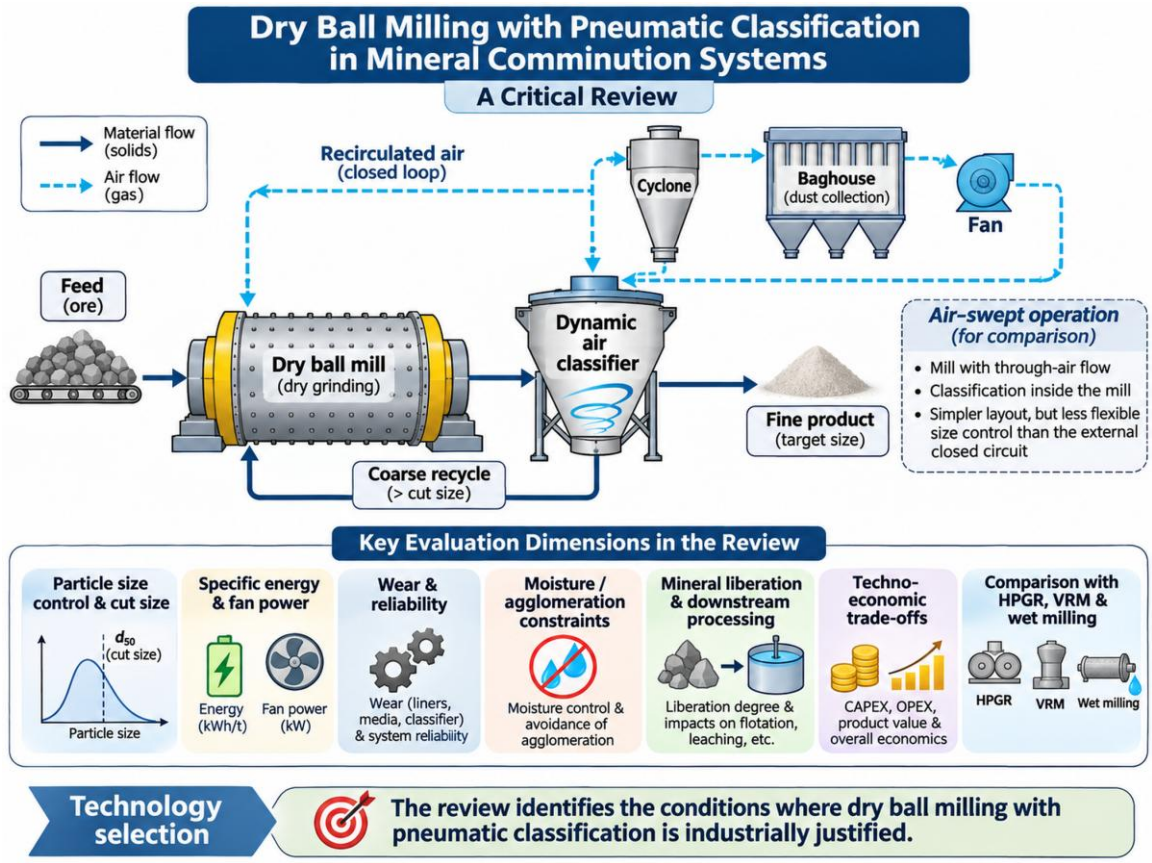
Highlights:

- Dry grinding circuits must be assessed at the complete system boundary.
- Classification selectivity governs circulating load and effective mill throughput.
- Moisture, mineralogy, and ultrafines generation define major operating constraints.
- Industrial technology selection requires comparable feed and product specifications.

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Graphical Abstract



1. Introduction

This study is a structured narrative critical review based on the REV06 bibliography supplied for manuscript preparation. The compendium comprised 148 candidate records, with an emphasis on 2020–2026, additional coverage reaching 2010, and 24 proposed search strings across 12 thematic areas. These descriptions characterize the supplied material, not a reproducible search performed for this article. The source compendium did not provide database identities, full search strings, a documented closing date, screening decisions, or a source-by-source full-text access log. The 148 candidate entries therefore must not be

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interpreted as 148 independently verified or comprehensively read full-text studies. No PRISMA-style systematic search, meta-analysis, or exhaustive verification is claimed.

1.1. Documentary basis, eligibility, and evidence interpretation

The unit of documentary analysis is the bibliographic entry and the claims associated with its stated topic, methods, and available bibliographic descriptors. The supplied list is the starting corpus; no retrospective database screening or full-text extraction procedure is reconstructed here. Entries relevant to tumbling-ball breakage, dry operation, aerodynamic classification, gas–solids handling, mineral liberation, scale-up, or full-circuit appraisal inform the narrative. Evidence on HPGR, VRM, stirred mills, wet circuits, cement, or non-ore powders is used only for comparison or mechanism discussion, not to directly validate the target mineral-ore plant. Where only bibliographic metadata are available, a paper is cited as contextual support, not as proof of a quantified outcome. The precise number of entries examined in full text, excluded or duplicated during original compendium assembly, and independently verified cannot be established from the supplied documentary record; none is invented. Consequently, assessments of coverage and the relative scarcity of audited integrated cases are confined to this compendium.

Four non-hierarchical relevance categories are used: (i) direct evidence—measurements on an integrated dry ball mill–pneumatic classifier circuit using a defined material and boundary; (ii) component-level evidence—tests of a mill, classifier, airflow, or dust subsystem; (iii) methodological evidence—measurement, modeling, partition-curve, balance, or scale-up methods applicable to the circuit; and (iv) comparative evidence—other grinding or classification technologies, materials, or downstream operations. These labels describe relevance to the target configuration, not study quality. The laboratory, pilot, industrial, and modeling categories in Table 3 are independent descriptors of investigation scale/type. An industrial study of a VRM, for example, may be comparative rather than direct evidence for a

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dry ball mill–classifier arrangement. The limited illustrative attribution in Table 3A is restricted to information identifiable in the cited entries; it is not a full-text extraction register.

The motivation for dry mineral comminution extends beyond eliminating process water. A dry grinding route can reduce slurry handling and subsequent dewatering duties, but replaces them with air movement, solids capture, moisture control, and dust-management obligations. A rigorous comparison therefore requires a common feed-to-product boundary and equivalent mineral recovery criteria.

Multisensor ore-sorting research provides context for feed variability and upstream process integration, but it does not establish the performance of the dry mill–classifier circuit considered here. (Adewuyi et al., 2025).

This review focuses specifically on a tumbling ball mill operated without bulk liquid, combined with an aerodynamic classifier. Two plant architectures must not be conflated: an air-swept mill uses process gas to withdraw the ground material from the mill, whereas an externally classified arrangement can use mechanical discharge followed by separately controlled airflow and a coarse-return circuit.

Comminution flowsheet design for narrow-vein mining raises a related question: how should energy use be compared when the feed preparation and product boundaries differ? (George et al., 2025).

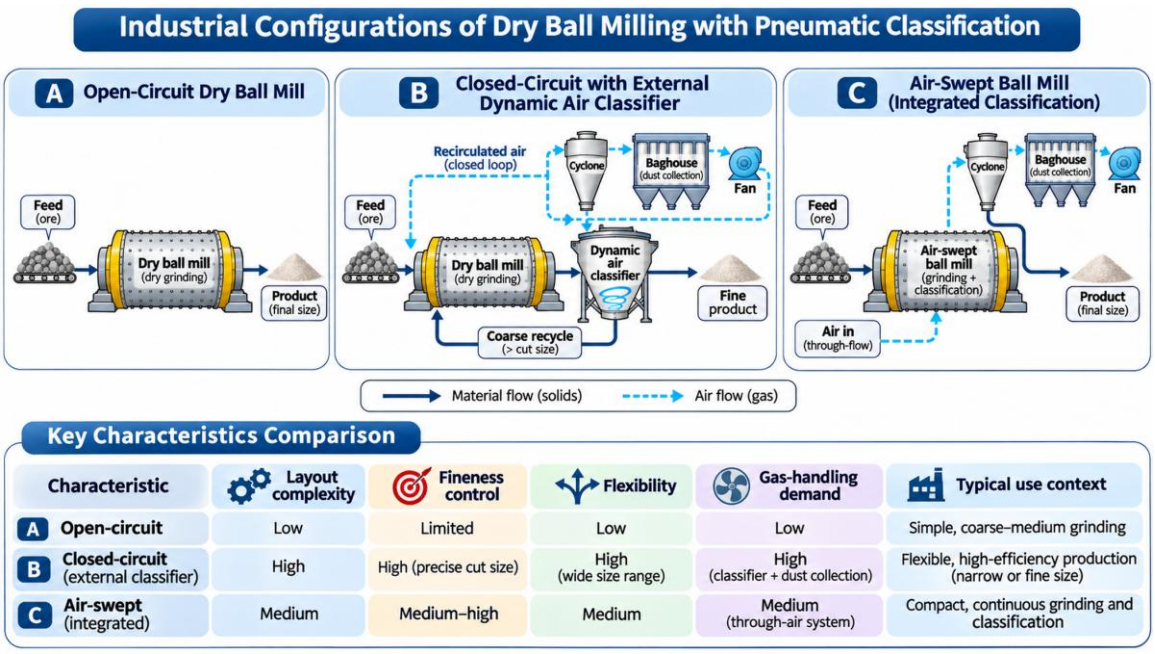
The five numbered figures and six tables (including Table 3A) translate the literature into a system-design framework. Figure 1 differentiates circuit elements, Figures 2 and 3 separate breakage from classification, Figure 4 defines the energy boundary, and Table 1 links ore properties to equipment choice. The key research question is under which conditions a complete dry ball mill–classifier plant is industrially competitive, rather than whether isolated components can attain a specified laboratory fineness.

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Studies coupling alternative breakage technologies with downstream gold flotation broaden the comparison beyond grinding energy. Their operating conditions are not automatically transferable to pneumatic classification of dry ball-mill products. (Thatipamula & Devasahayam, 2025).

Figure 1 compares the three circuit arrangements examined in this review and shows how mill discharge, pneumatic separation, coarse-particle recycle, and air handling differ.



Characteristic	Layout complexity	Fineness control	Flexibility	Gas-handling demand	Typical use context
A Open-circuit	Low	Limited	Low	Low	Simple, coarse–medium grinding
B Closed-circuit (external classifier)	High	High (precise cut size)	High (wide size range)	High (classifier + dust collection)	Flexible, high-efficiency production (narrow or fine size)
C Air-swept (integrated)	Medium	Medium–high	Medium	Medium (through-air system)	Compact, continuous grinding and classification

Figure 1. Comparison of open-circuit dry ball milling, closed-circuit milling with external pneumatic classification, and air-swept milling arrangements.
Note. Conceptual infographic prepared for this review; original artwork provenance should be confirmed from the source files. Diagrams, curves, and comparison ratings are illustrative, not calibrated to a specific industrial plant.

The configurations differ in solids withdrawal, gas duty, and classification control location; they should not be ranked without matched ore and product specifications.

2. Fundamentals of Dry Ball Milling

Breakage in tumbling mills emerges from impact, compression, abrasion, and particle–media interactions; individual contributions vary with mill speed, filling, liner profile, feed

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size, and media size distribution. In a dry charge, the absence of slurry changes particle transport, cushioning, adhesion, and the buildup of fine material on media and liners. Figure 2 distinguishes desirable fragmentation from the progressive agglomeration that can deteriorate fine-grinding performance.

Studies of closed-circuit control, dry grinding aids, media stresses, and energy transfer address distinct mechanisms rather than demonstrating integrated plant performance (Al Bannoud et al., 2022; Bwalya et al., 2025; Cayirli, 2022; Doroszuk et al., 2024a, 2024b).

Bond-test variability, mineral-mixture kinetics, media geometry, and media-review literature illustrate why grindability should not be reduced to a single equipment-independent index. (González García et al., 2021; Gupta, 2020; Liao et al., 2022; Matsanga et al., 2023).

Predictive closed-circuit modeling, nonstandard work-index testing, liner wear, and particle breakage each address distinct pieces of the milling problem (Muanpaopong et al., 2023a, 2023b; Nikolić et al., 2025; Pural et al., 2024; Soares et al., 2025).

Power estimation, ore-specific media motion, and alternative ball geometries add useful modeling perspectives. Their relevance to dry industrial circuits depends on comparable feed characteristics and mill conditions. (Wang et al., 2026; Yang et al., 2022; Zhou et al., 2026).

The Bond work index remains useful for preliminary communication of ore grindability, but it does not predict an air-classified fine-grinding circuit independently of equipment. Feed preparation, grind size, circuit efficiency, and moisture-related cohesion must be reconciled with the specific test protocol. Population-balance approaches are more transferable when you recalibrate breakage and selection functions for the actual solids mixture and operating regime.

Experimental breakage tests and grinding-media studies offer complementary evidence on ore response, particle size, and potential downstream effects; distinguish results by test scale

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and material. (Bueno et al., 2023; Can & Başaran, 2023; Cayirli & Gokcen, 2021; Elbendari & Ibrahim, 2025).

Reliability models, lignite particle morphology, ceramic-media loading, and approaches beyond nominal energy input point to a wider operating envelope than mill power alone. (Gu et al., 2026; Guven et al., 2023; Ling et al., 2026; Moussaoui & Ould Hamou, 2026).

Corrected Bond methods, mill acoustic measurements, multicomponent liberation models, and rotational-speed tests illuminate different aspects of scale-up; none independently closes a full dry-circuit balance. (Nikolić et al., 2022; Owusu et al., 2021; Rocha et al., 2025; Tang et al., 2024).

Magnetite media and ceramic-media investigations may inform material-specific screening, but researchers must check reported experimental conditions and results before numerical transfer (Wu et al., 2024; Yuan et al., 2023a, 2023b).

Grinding aids may modify surface adhesion and dry powder flowability. Still, the evidence for calcite or other industrial minerals cannot be taken as a quantitative guarantee for chromite or sulfide-bearing ores. Changes in product shape, chemical surface state, and iron pickup from media must be investigated alongside specific grinding energy.

Dry-mill operating tests, alternative breakage assessments, and cement-mill energy analyses are pertinent benchmarks, provided their distinct feed and circuit conditions are clearly stated. (Bueno et al., 2024; Cayirli, 2018; Chehreh Chelgani et al., 2025; Ghalandari & Iranmanesh, 2020).

Research on solids concentration, impact loads, milling mechanisms, and liner configurations underscores the coupling between powder transport and the mechanical environment. (Guo & Guo, 2024; Kalala et al., 2022; Martelli & Di Nunzio, 2025; Muanpaopong et al., 2022).

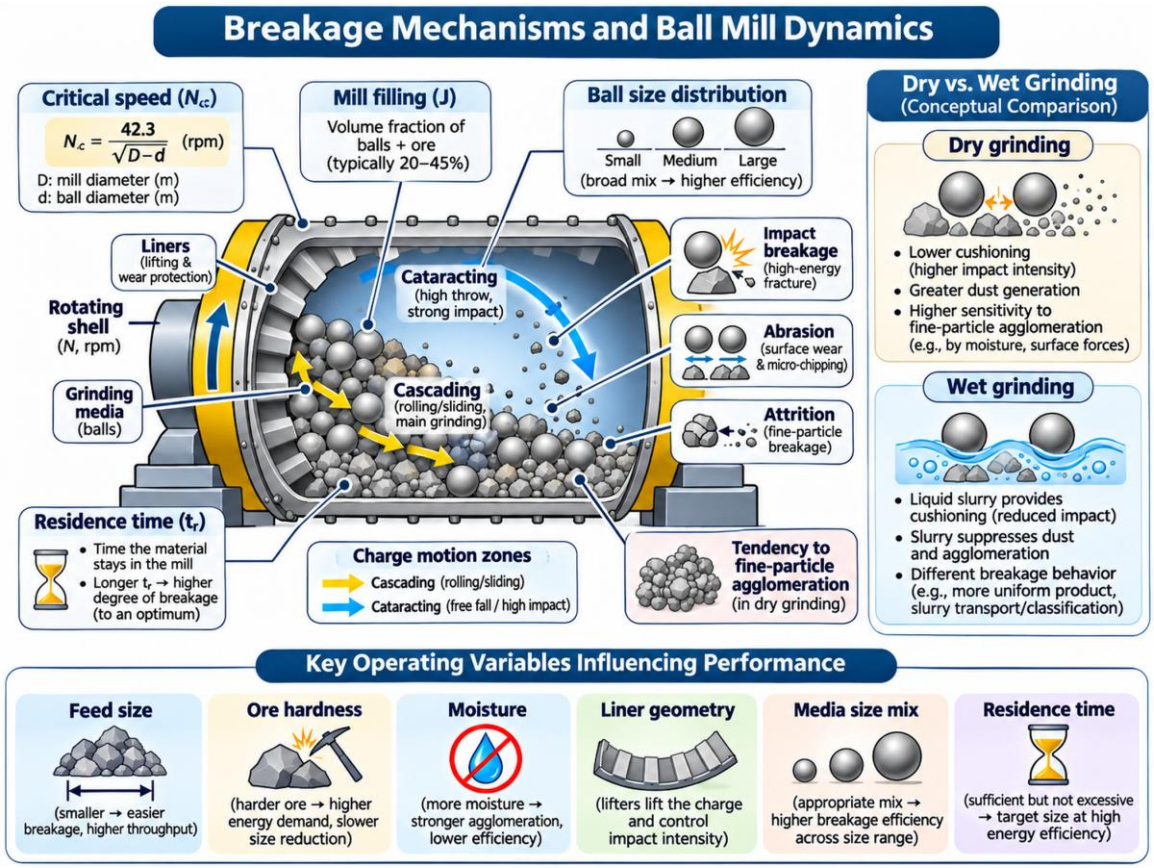
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Work-index estimation and tests of different media sizes and compositions inform preliminary selection, yet ore mineralogy and downstream specifications still govern their practical value. (Nikolić et al., 2024; Petrakis & Komnitsas, 2022; Sanches et al., 2023; Tong et al., 2023).

Automatic ball addition and ceramic-media configuration illustrate charge-management questions for further testing (Wu et al., 2026; Yuan et al., 2023a, 2023b).

Figure 2 summarizes the relevant dry-milling breakage mechanisms and charge dynamics, highlighting the operating variables that may promote size reduction or fine-particle agglomeration.



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Figure 2. Breakage mechanisms, charge dynamics, operational variables, and conceptual differences between dry and wet ball milling.
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The mechanism map illustrates plausible interactions rather than measured contributions to breakage or wear; tests on the intended feed are still required.

3. Pneumatic Classification Fundamentals and Technologies

A pneumatic classifier partitions particles by the combined effects of aerodynamic drag, centrifugal forces, particle inertia, and residence-time distributions. The classifier is not an ideal sieve: cut size, sharpness, bypass, and coarse contamination of fines must all be characterized using size-dependent partition curves, rather than a single nominal d_{50} value.

Classifier chamber geometry, rotor-flow instabilities, and fine-powder separation limitations frame the aerodynamic design problem. Published component studies cannot be treated as direct plant guarantees. (Abohelwa et al., 2023; Chan et al., 2026; Huang et al., 2023; Li et al., 2025).

Comparisons between air classifiers and hydrocyclones, together with flow-field experiments, reinforce the need to define a common classification metric before ranking alternatives. (Tipici et al., 2024; Yuan et al., 2024).

Rotor speed and airflow should be interpreted jointly. Increasing rotor speed may lower a cut size under otherwise comparable conditions, but pressure loss, fines short-circuiting, loading, and feed variability can alter the response. Static, zigzag, and dynamic rotor configurations are consequently not interchangeable based on catalog capacity alone. Figure 3 uses the partition-to-fines convention: the ordinate is the fraction reporting to fine product at each particle size. The complementary partition-to-coarse probability is $1 - P^f(d)$. Smaller coarse misplacement at fine sizes and smaller fines contamination at coarse sizes indicate sharper separation, subject to the specified bypass convention.

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Feed blending, rotary classifier hydrodynamics, baffle arrangements, and particle-motion models influence particle partitioning in distinct ways; their relative importance varies with operating point. (Altun, 2022; Huang et al., 2024; Li et al., 2022; Liu & Yu, 2025).

Secondary-air vanes and guide-vane configurations affect the internal flow paths examined in classifier design studies. Industrial conclusions still require measured cut curves and pressure drops. (Wang et al., 2025; Zeng et al., 2022).

The classifier also affects the mill indirectly. Poor cuts or unstable solids loading increase unnecessary recycling, increase fan duty, and change residence-time and heat-generation patterns. Industrial characterization should report airflow, temperature, dust loading, rotor speed, pressure loss, partition curve, and feed/product size distributions on a consistent mass basis.

Two-phase simulation, cone geometry, vortical structures, and classification mechanisms can clarify gas–solid behavior, but model predictions require experimental corroboration at relevant loadings. (Bagherzadeh et al., 2024; Huang et al., 2023; Li et al., 2022; Sun et al., 2022).

Cyclonic flow observations and numerical work on alternative classifier arrangements extend the geometric evidence base without removing the need for plant-specific calibration. (Yan et al., 2024; Zhou et al., 2024).

Figure 3 depicts the classifier and conceptual partition-to-fines functions $P^f(d)$, declining with increasing particle size. Its illustrative d_{50} occurs where $P^f(d_{50}) = 0.5$. On this convention, fine-particle bypass to coarse reject corresponds to $1 - P^f$ at small d, while misplaced coarse material in final fines corresponds to P^f at large d. The curves are illustrative rather than fitted industrial observations.

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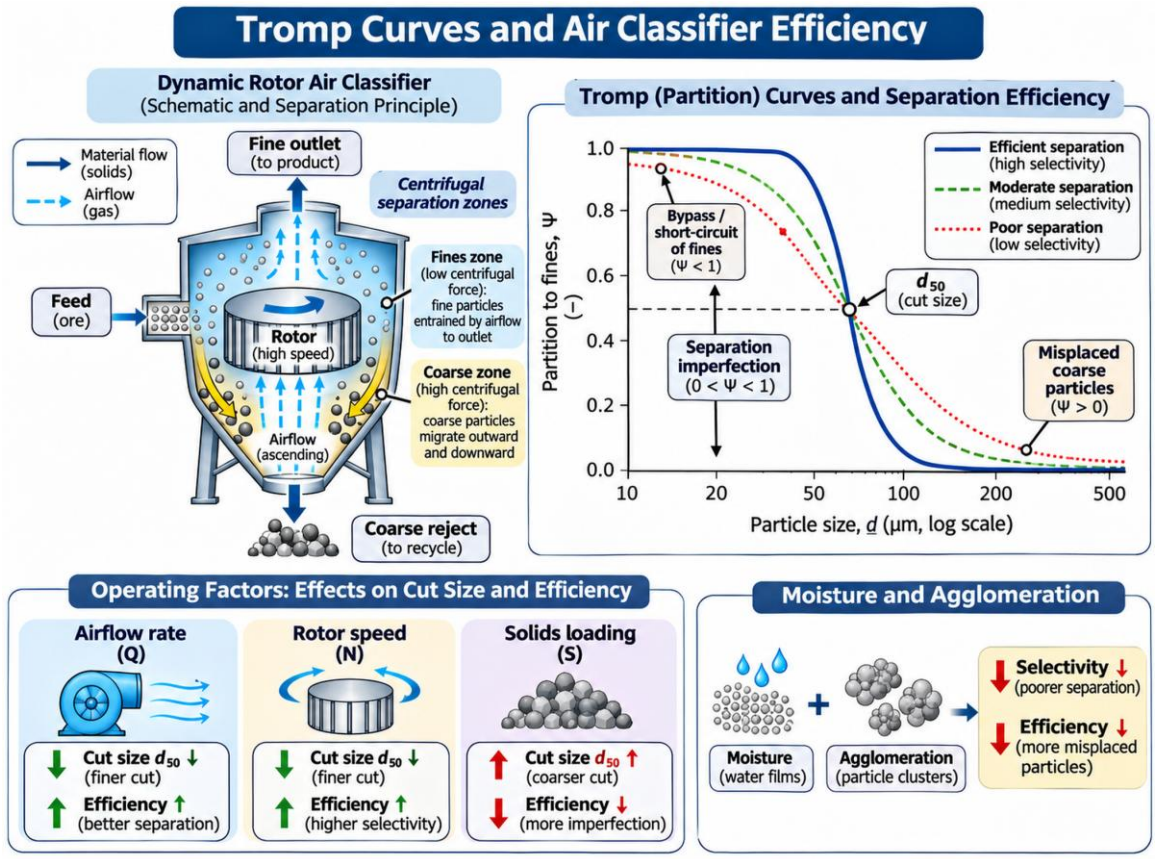


Figure 3. Dynamic air classifier and illustrative partition-to-fines curves, $P^f(d)$, showing d_{50}, fine bypass to coarse reject, and coarse misplacement into the fine product.
Note. The plotted functions use the fraction reporting to fines, $P^f(d)$; the corresponding coarse fraction is $1 - P^f(d)$. All curve parameters are hypothetical, not calibrated for equipment sizing.

The drawn partition curves are illustrative. Obtain numerical bypass, efficiency, and cut-size values from a measured, mass-reconciled test.

4. Dry Ball Mill–Air Classifier Circuit Configurations

Open-circuit dry ball milling simplifies solids handling but offers limited independent control of particle size distribution. A closed-circuit external classifier decouples breakage from aerodynamic sorting, but requires coarse-return conveying and additional gas–solid

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equipment. Figure 1 presents the basic material-flow relationship, including the indispensable coarse return and final solids collection elements.

Closed-circuit simulations and industrial separation comparisons highlight the importance of distinguishing the classifier's own efficiency from the resulting mill-circuit throughput. (Costa et al., 2024; Muanpaopong et al., 2023).

Air-swept milling removes solids with process gas and therefore intertwines internal transport, evaporation, breakage, and classification load. In contrast, a mechanically discharged mill with an independent classifier may permit more independent tuning of mill residence time and classification air velocity. However, without matched feed characteristics and measured overall specific energy, neither option can be ranked.

Grinding-circuit data analytics and investigations of alternative classification systems are relevant to operational control, although they concern different processing arrangements. (Di Feo et al., 2024; Ozcan, 2022).

At steady state and on a dry-solids basis, a circuit boundary enclosing the mill, classifier, cyclone, baghouse and return conveyors satisfies $F = P + L$, where F is fresh dry feed, P is all on-spec final dry product leaving the boundary, and L is measured net dry-solids loss or off-spec withdrawal. Coarse reject C is an internal recycle and cancels from the overall balance. For a mechanically discharged mill with only fresh feed and classifier coarse reject entering the mill, inlet throughput is $M_{in} = F + C$; if collector solids or other streams return upstream of the inlet meter, include those returns as well. Cyclone and baghouse solids should be individually routed and recorded as product, recycled feed, off-spec withdrawal, or loss. Mill outlet throughput is not automatically equal to inlet throughput if side streams or hold-up changes occur. Gas, water vapor, leakage, and thermal balances are established separately and reconciled with captured dust and evaporation.

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Closed-loop dry HPGR classification and industrial ball-mill residence-time work provide useful analogies for recycle modeling, not a substitute for direct dry ball-mill measurements. (Jankovic et al., 2015; Vinnett et al., 2022).

5. Ore Characteristics and Industrial Applicability

Iron-ore pretreatment, dry-processing methods, population-balance modeling, and flotation-related grinding conditions collectively show why mineral response and downstream chemistry belong in the assessment. (Adewuyi et al., 2024; Chehreh Chelgani & Asimi Neisiani, 2022; de Jong, 2024; Judge et al., 2025).

Phosphorus-bearing iron ores and fine-ore grinding illustrate mineral-specific feed constraints. The review treats their treatment as feed characterization rather than a universal dry-milling advantage. (Pereira, 2026c; Zhang et al., 2024).

Chromite merits a separate assessment because high particle density, abrasive gangue, and liberation requirements for subsequent physical or chemical processing may affect both airflow classification and permissible ultrafines production. The presence of a dry ball mill in an industrial mineral process does not establish suitability for a particular chromite concentrate without testwork on mineral assemblage, feed moisture, target size, and downstream recovery.

Grinding aids, electrostatic separation, mineralogical effects, and liberation-related breakage parameters represent different pathways through which feed properties shape a dry process flowsheet. (Cayirli et al., 2023; Coelho & Leal Filho, 2025; Deniz, 2022; Nghipulile et al., 2022).

Phosphorus-removal literature shows how beneficiation requirements can determine the acceptable grinding product, even before selecting a particular mill. (Pereira & Papini, 2015).

Feedstock pretreatment and ore sorting can shift the grinding energy and product chemistry boundary. Such work may improve overall flowsheet outcomes but does not, by

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itself, demonstrate higher performance of a ball mill–classifier combination; comparative evidence must be labeled accordingly.

Calcite grinding-aid trials, industrial grinding control, selective comminution, and liberation-based recovery assessments illustrate distinct criteria for selecting ore-dependent routes. (Cayirli et al., 2026; Costa et al., 2025; Guldris Leon & Bengtsson, 2022; Pereira, 2026a).

Research linking grinding conditions with flotation of semi-soluble minerals warrants attention to downstream chemistry, not just the nominal particle-size target. (Pereira et al., 2023).

Table 1 consolidates the ore-characterization and testwork evidence required to judge whether dry milling and pneumatic classification are technically applicable to a specific feed.

Table 1. Ore properties and minimum evidence requirements

Parameter	Required evidence	Decision significance
Moisture	Free/surface moisture; hygroscopicity	Adhesion and gas load
Mineralogy	Quantitative phases and liberation	Breakage and product quality
Grindability	Bond test and dry pilot tests	Mill sizing
Abrasivity	Media/liner wear test	Maintenance and contamination
Density / PSD	Size-dependent mineral density	Classifier calibration

Note. Original critical synthesis, not published numeric operating data.

6. Energy Efficiency and Thermal–Fluid Performance

The relevant metric is complete-circuit electrical and thermal demand divided by saleable dry product mass, not the mill motor reading alone. The accounting boundary must include mill drive, classifier rotor, fans, conveying equipment, filtration, and any required drying or thermal conditioning. Figure 4 presents these terms without implying universal energy fractions.

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Thermal pretreatment, grindability prediction, calcite aids, and structural changes during grinding provide different ways to interpret specific energy. Comparisons require matching material and treatment history. (Asgari & Huang, 2025; Ghadernejad et al., 2026; Katircioglu-Bayel, 2023; Li et al., 2014).

At equal target fineness, pressure drop across the ducts, classifier, cyclone, and baghouse drives ventilation demand. Gas recirculation can reduce thermal duty but may accumulate humidity and ultrafines, altering separation. Consequently, energy measurements are incomplete unless they record airflow, temperature, humidity, pressure, and solids loading alongside throughput.

Grinding-aid utilization, industrial VRM exergy analysis, particle-size descriptors, and ore-circuit optimization show how strongly the accounting boundary influences apparent energy performance. (Cayirli et al., 2026; Ghalandari et al., 2021; Lai et al., 2025; Wu et al., 2025).

For energy comparisons, the reference denominator is the mass of on-specification, saleable dry product exported across the defined circuit boundary, $m_{saleaβle}$ (t). Gross electrical specific consumption is $SEC_{el} = \Sigma E_el / m_{saleaβle}$ (kWh_el/t), incorporating mill, classifier, fans, conveyors, dust capture, controls, and other relevant drives. Thermal specific demand is SEC_{th} = Q_imported / $m_{saleaβle}$ (MJ_th/t), including fuel or imported heat for required drying/conditioning and identifying whether lower heating value or another energy basis is used. Do not add these two numbers without documenting an energy-conversion convention; if total input energy is required, $SEC_{total} = SEC_{el} \times 3.6 + SEC_{th}$ (MJ_input/t), with electrical and thermal inputs reported separately and no implied primary-energy equivalence. Rejects, losses, and off-spec material are excluded from the saleable-product denominator, but their processing energy remains within the numerator. This definition must be applied consistently to all compared routes.

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Media composition, operating conditions, product-size prediction, and energy-saving grinding designs matter for optimization; reported mechanisms should not be merged into a single generic efficiency claim. (Fang et al., 2024; Guo et al., 2022; Lee et al., 2024; Zhang et al., 2022).

Figure 4 establishes the complete-circuit energy-accounting boundary, including grinding, classification, ventilation, collection, conveying, and thermal-conditioning duties.

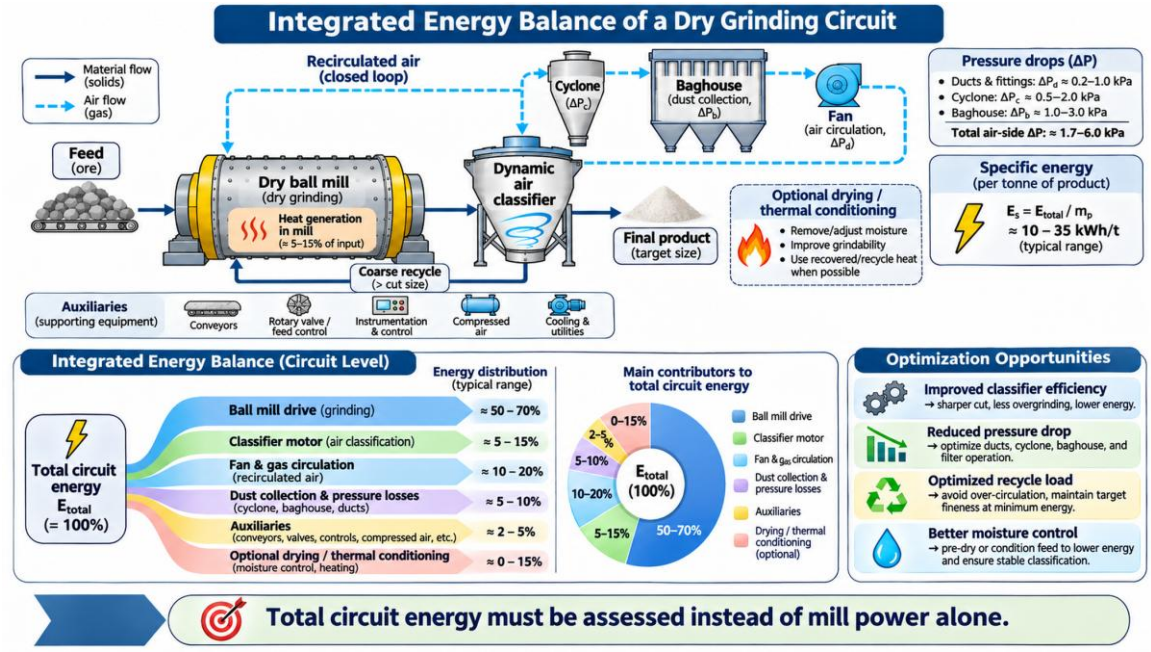


Figure 4. Integrated energy-accounting boundary for dry ball milling with pneumatic classification, including grinding, fans, separation, auxiliaries, and thermal conditioning.
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Table 2 defines the minimum operating indicators for reporting dry grinding-circuit performance on a consistent fresh-feed, recycle, classification, and energy basis.

Table 2. Integrated circuit performance reporting checklist

Indicator	Unit	Definition
Fresh feed	t/h dry	Net new dry solids crossing the circuit inlet

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Mill inlet throughput	t/h dry	Fresh dry feed + coarse classifier return + any other measured returns entering the inlet
Circulating load	%	Classifier coarse return / fresh dry feed × 100; identify sampling points
Classifier cut d_{50}	µm	Particle size at P_f(d) = 0.5 for the partition-to-fines convention
Electrical SEC	kWh_el/t saleable dry product	Total metered circuit electricity / on-spec saleable dry product
Thermal SEC	MJ_th/t saleable dry product	Imported thermal energy for drying/conditioning / on-spec saleable dry product
Off-spec and losses	t/h dry	Separate exported rejects, dust losses and recoveries; reconcile dry-solids balance

Note. Original reporting framework; no site-specific values assumed.

7. Equipment Design, Wear, Reliability, and Process Safety

Dry abrasive feed presents design challenges in lining wear, ball consumption, seals, bearings, pneumatic duct elbows, classifier rotor edges, and dust collection. Reliability depends on maintaining a controlled circuit pressure profile and protecting rotating elements from dust ingress and high-temperature excursions.

Media-action control and grinding-media shape studies connect mechanical design to both breakage and separation behavior. Their implications must be tested with the intended mineral feed. (Baigereyev et al., 2025; Ren et al., 2023).

Dust collection is a core process and occupational-control duty. Baghouse sizing should document actual gas flow, operating temperature, filter media, filtration velocity (air-to-cloth ratio), dust loading and size distribution, allowable pressure drop, cleaning method, dust discharge, and combustible/reactive-dust hazards, where applicable. Dust electrical resistivity is principally relevant when evaluating electrostatic precipitators and is not a universal

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baghouse sizing variable. Hazard analysis must be material-specific; mineral dusts are not uniformly combustible.

Work on grinding-media chemistry in gold extraction and on hard-rock grinding provides separate evidence streams for media choice, wear, and potential product contamination. (Niu et al., 2025; Tan et al., 2025).

Process instrumentation should include feed rate, mill drive load, differential pressures, fan duty, classifier speed, temperatures, and dust collector performance. Interlocks should manage loss of airflow, high temperature, abnormal vibration, dust discharge blockage, and circuit pressure excursions. Maintenance planning should compare erosion and wear costs at equal product specifications.

Mechanical activation and media-system selection extend the evaluation from particle size toward surface changes and equipment performance, with process-specific validation still essential. (Pereira, 2026b; Wang et al., 2024).

8. Downstream Mineral Processing and Product Quality

Grinding is a liberation step, not merely a particle-size reduction target. Overproduction of ultrafines can adversely affect downstream gravity, electrostatic, magnetic, or flotation circuits, while insufficient liberation can suppress recovery even when a nominal d80 target is achieved. The correct endpoint is therefore a product-size and mineral-liberation specification tied to metallurgical performance.

Deflector-wheel classification, classifier flow dynamics, and flotation conditioning studies span both powder separation and downstream processing. They should be interpreted as complementary rather than identical operations. (Abohelwa et al., 2024; Huang et al., 2024; Tanhua et al., 2022).

Dry and wet grinding can generate different surface states and collector interactions, particularly for sulfides. Evidence from flotation tests should not be reinterpreted as proof that

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dry pneumatic classification itself improved recovery. The relevant causal chain must separate media chemistry, oxidation, reagents, size distribution, and subsequent wet conditioning.

Chalcopyrite surface reactivity, quartz flotation aids, and grinding-media shape highlight potential downstream sensitivity to how the grinding product is generated. (Amos-Judge et al., 2026; Mao et al., 2022; Wang et al., 2025).

Attrition and media wear can contaminate products with iron and other elements, constraining industrial minerals and selective hydrometallurgical leaching. Any apparent grinding benefit must be offset against downstream losses, additional reagent consumption, or purification requirements.

Galena grinding studies, flotation-oriented grinding models, and ceramic-media investigations relate particle-size control to downstream response. A matched product comparison is essential. (Guo et al., 2025; Mathe et al., 2021; Zhang et al., 2021).

9. Modeling, Simulation, Scale-Up, and Process Optimization

A credible scale-up architecture couples a population-balance model for breakage with experimentally calibrated classifier partition functions and a pressure-loss / airflow model. The return stream cannot be prescribed independently of the classifier cut because both circulating load and size distribution are endogenous circuit outputs.

Predictive mill operation, digital-twin calibration, full-scale numerical modeling, and classifier optimization form a diverse model-validation literature with different underlying datasets. (Altun et al., 2026; Doroszuk, n.d.; Ho et al., 2025; Huang et al., 2026).

Ball-charge optimization, rotor-classifier operation, and HPGR performance evaluations inform component-level scale-up. Their results require reconciliation within the intended complete circuit. (Luo et al., 2026; Peng et al., 2024; Saramak & Saramak, 2024; Wei et al., 2025).

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Charge-motion simulation and ore-specific kinetic optimization describe complementary modeling levels; neither alone predicts pneumatic transport or whole-plant availability. (Yin et al., 2024; Zhang et al., 2026).

Computational fluid dynamics can characterize velocity fields, recirculation zones, and cyclone or rotor geometry, whereas discrete-element approaches can inform charge motion and contact environments. Neither model, on its own, demonstrates final mineral recovery or circuit energy advantage. Feed loadings, particle density distributions, and pilot or industrial calibration should bound model applicability.

Size-reduction kinetics, computational fluid dynamics, and dynamic-classifier investigations represent different model domains. Their coupling requires independently validated boundary conditions. (Austin & Schneider, 2022; Esmaeilpour et al., 2024; Ho et al., 2024; Jia et al., 2021).

Grinding-law optimization, mineral-process scale-up, vortex-finder geometry, and stirred-mill evaluation broaden the modeling toolkit but do not eliminate the need for ore- and equipment-specific calibration. (Ma et al., 2022; Pereira, 2026d; Sun et al., 2021; Wei et al., 2026).

Mechanochemical kaolin experiments inform milling-induced transformation, although their purpose differs from routine industrial size reduction and classification. (Őze & Makó, 2023).

Digital control may reduce product-size excursions as ore properties change. However, claims about predictive algorithms must be compared with conventional control under the same disturbances; performance gains in wet stirred or alternative mill circuits cannot be transferred numerically to dry ball milling without validation.

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Pressure-loss prediction, guide-cone design, multiphase measurements, and zigzag-classifier reviews jointly frame the aerodynamic validation needed beyond a nominal cut size. (Betz et al., 2022; Ho et al., 2024; Huang et al., 2024; Kaas et al., 2022).

Dry treatment of spent battery materials, classification reviews, turbo-classifier simulation, and hybrid circuit models reflect the breadth of current applications rather than one standardized flowsheet. (Mulet-Mery et al., 2026; Pukkella et al., 2023; Sun et al., 2021; Yang et al., 2024).

Numerical optimization of turbo-classifier flow offers further design context; experimental pressure and separation measurements remain necessary for reliable engineering use. (Zeng et al., 2020).

Table 3 distinguishes laboratory, pilot, industrial, and model-based evidence to clarify what each evidence level can and cannot establish about technology readiness. Table 3A provides examples of evidence relevance; the classification is independent of laboratory/pilot/industrial/modeling scale and does not represent a quantitative quality score.

Table 3. Levels of evidence for technology appraisal

Evidence	Strength	Main limitation
Laboratory grinding	Mechanisms/tendencies	No plant balances
Pilot closed circuit	Integrated behavior under test conditions	Scale-dependent pressure and wear
Industrial case history	Operational feasibility	Confounding feed and product differences
Comparative modeling	Scenario exploration	Assumption dependence

Note. Original critical assessment derived from the supplied literature categories.

Table 3A. Illustrative source-to-claim traceability matrix (bibliographic-level appraisal)

Reference	Material/configuration	Scale or evidence type	Supportable claim/information basis	Transfer boundary
Al Bannoud et al. (2022).	Dry closed-circuit ball milling	Methodological; predictive control	Study topic identifies neural-network-based circuit control; bibliographic description only.	No industrial ore-specific performance inferred

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Muanpaopong et al. (2023b).	Cement clinker; closed ball mill and Tromp curve	Methodological / component	Study title describes population-balance modeling with variable classifier partition.	Cement model does not establish dry mineral-ore results.
Abohelwa et al. (2023).	Fine powder; turbo air classifier	Component-level	Study topic concerns separation performance limits	Classifier-only scope; mineral-ore circuit not shown
Sun et al. (2022).	Horizontal three-rotor-cage air classifier	Component-level	Study title identifies aerodynamic mechanisms and classification assessment.	Different classifier/material and system boundary
Cayirli (2018)	Dry ball mill tests	Component-level	Study title evaluates mill operating parameters	No integrated pneumatic classifier evidenced by title
Ballantyne & Lane (2022).	Dry VRM or HPGR versus wet milling	Comparative; conference contribution	Examines alternative circuit architectures	Cannot quantify dry ball mill–classifier advantage
Yuan et al. (2024).	Disturbing rotary centrifugal air classifier	Component-level; experimental/simulation	Title identifies measured and modeled internal flow field	Not an integrated dry ball-mill plant

Note. This table is an explicitly limited attribution matrix, not a full-text systematic extraction. Entries, titles, and topics are identifiable in the supplied bibliography. Scale or experimental detail not established in that record is not asserted, and no numerical outcome is imported. No listed study is labeled direct integrated mineral-ore plant evidence without supporting documentation.

Table 3A should be read as a documentary mapping of source topics to the review questions, not as independent confirmation of performance, experimental scale, or industrial readiness. Because the underlying full-text access history is unavailable, no evidence-strength ranking or quantitative transfer factor is assigned to individual records.

10. Techno-Economic and Environmental Assessment

Dry route economics include grinding and classification investment, solids handling, dust capture, air conveying, maintenance, auxiliary heat, and outage-related costs. Savings in

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makeup water and dewatering infrastructure are material where water infrastructure is limiting, but cannot be counted without correctly identifying downstream water use.

Grinding-environment effects on copper-sulfide flotation illustrate why environmental and economic boundaries should include the subsequent separation stage when relevant. (Bruckard & Sparrow, 2024).

Techno-economic comparison requires a common throughput, fineness, product recovery, plant availability, utility prices, and equipment life. An identical grinding power index does not entail an identical cost structure: dry filtration and air-handling maintenance may dominate in some applications. In contrast, slurry transport and filtration influence the wet benchmark.

Geometallurgical economic analysis links ore variability to project outcomes, supporting scenario-dependent rather than generic plant costs. (Freire da Silva et al., 2026).

Environmental appraisal should extend to source-specific electricity emissions, dust loss, consumables, water withdrawal, and embodied equipment burdens. A robust life-cycle assessment must avoid claiming a universal dry-route carbon advantage without plant-specific energy and upstream grid assumptions.

11. Critical Synthesis and Technology Selection

The central evidence gap is not that dry milling or air classification is unproven individually; it is the limited comparability of integrated mineral-ore circuit reports using a uniform process boundary. A wet ball mill, an HPGR plus air-classifier circuit, a vertical roller mill, and a dry ball mill plus external classifier differ in breakage mechanism, feed moisture tolerance, control structure, and auxiliary duties. Figure 5 intentionally uses qualitative attributes rather than invented plant benchmarks.

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Comparisons of comminution technologies and wet-versus-dry milling provide context for technology screening, but differences in machine type and feed prevent direct ranking without normalization. (Baawuah et al., 2020; Ogonowski et al., 2018).

Table 4 sets out a screening framework: site-specific water constraints, achievable cut-size sharpness, feed moisture, abrasive wear, product liberation, and demonstrated supplier capability are coequal selection criteria. A multi-criteria decision should prioritize measurable constraints over vendor brochure capacities and avoid assigning technology readiness levels from isolated component papers.

Dry VRM/HPGR comparisons and flotation-feed characterization point to the importance of evaluating energy, liberation, and surface chemistry at a matched flowsheet boundary. (Ballantyne & Lane, 2022; Peltoniemi et al., 2020).

On this basis, dry ball milling with pneumatic classification is most defensible for suitably dry, characterized feeds where independent cut-size control supports the required product distribution and where avoiding slurry infrastructure offsets extra fan and dust-control burdens. It is less defensible where cohesion or moisture degrades classification, ore abrasion drives high maintenance, or downstream recovery depends on a wet-conditioned surface state.

HPGR-induced microcracking and subsequent milling performance belong in the comparative evidence base, provided pretreatment effects are not attributed to pneumatic ball-mill classification. (Nghipulile et al., 2023).

Figure 5 compares the candidate comminution routes through a qualitative technology-selection matrix, emphasizing the trade-offs that require ore-specific verification rather than assumed universal rankings.

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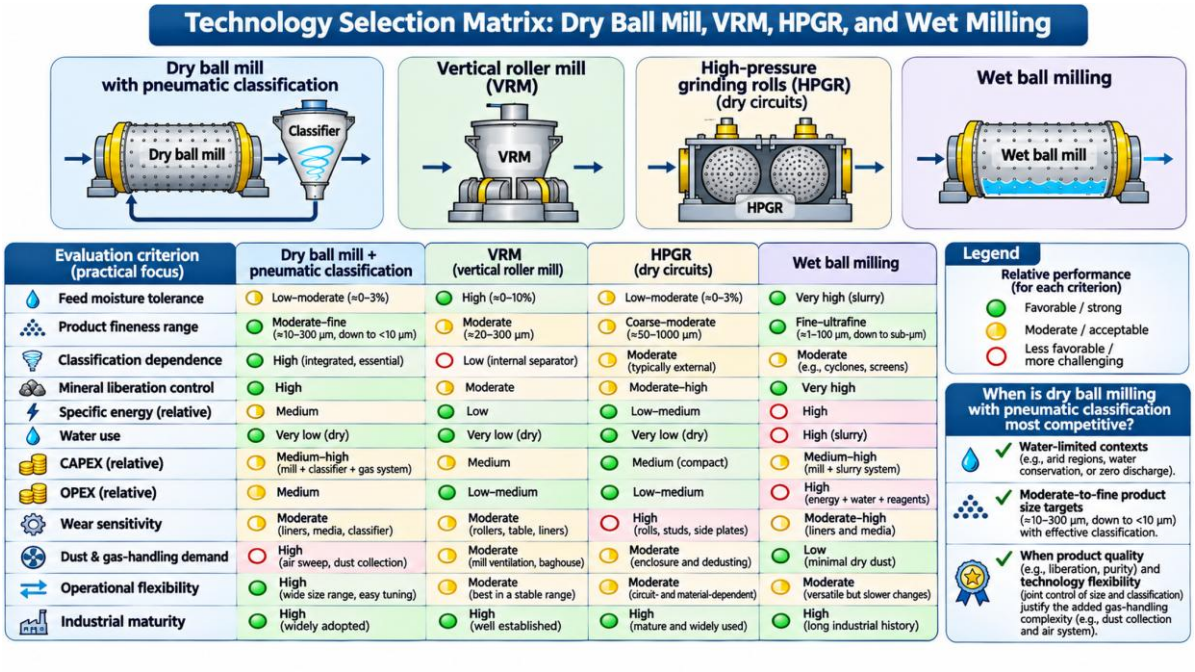


Figure 5. Conceptual multicriteria technology-selection matrix comparing dry ball milling with pneumatic classification, VRM, HPGR, and wet milling.
Note. Qualitative synthesis prepared for this review; artwork provenance should be confirmed from source files; categories are context-dependent, not quantitative performance rankings.

Table 4 translates the preceding comparison into measurable screening criteria and identifies major exclusion risks for preliminary technology selection.

Table 4. Technology-selection framework

Criterion	Minimum comparison basis	Exclusion/risk flag
Feed moisture	Same feed-condition definition	Cohesion and agglomeration
Fineness and liberation	Same product PSD and mineral liberation	Uncontrolled ultrafines
Total energy	Metered whole circuit	Uncounted fan/dryer power
Reliability	Availability and wear replacement	Abrasive mineral phases
Life-cycle cost	Same operating life and discount basis	Hidden auxiliaries

Note. Original screening matrix; site-specific CAPEX/OPEX figures are intentionally not invented.

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12. Future Research Directions

Future research should report independently audited industrial data with complete air and solids balances, normalized product fineness, classification curves, and whole-circuit electrical consumption. Controlled experiments need to isolate moisture, mineral density, feed-size distribution, and coarse recycle rather than altering several variables simultaneously.

The proposed engineering evidence package includes representative ore characterization, dry grindability, pilot partition curves, pneumatic resistance, dust capture, media wear, downstream liberation tests, and common-boundary energy and economic evaluations. Table 5 identifies the corresponding research priorities and sources of uncertainty.

Table 5 summarizes the principal research gaps, the corresponding experimental validation actions, and the engineering decisions that those investigations should support.

Table 5. Research priorities and validation needs

Gap	Experimental action	Decision output
Industrial energy balance	Meter total mill/fan/classifier/filter loads	Comparable SEC
Moisture sensitivity	Vary feed water content under controlled operation	Stable operating envelope
Chromite testwork	Dry grindability, abrasion, and liberation	Ore-specific feasibility
Classifier scale-up	Measure Tromp curve and pressure loss at multiple loads	Validated cut and fan power
Downstream interaction	Matched flotation/separation tests	Net recovery effect

Note. Original recommendations based on gaps in the source compendium.

13. Conclusions

Dry ball milling combined with pneumatic classification is a technically plausible option for suitably characterized mineral feeds. However, this review does not establish universal competitiveness or validate a particular industrial design. The most defensible contribution is a circuit-wide appraisal framework: dry-solid and gas balances, measured classifier partition curves, separately reported electrical and thermal specific demand, dust

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collection and wear, and saleable-product liberation and recovery. Component and analogous-technology findings provide relevant mechanisms but cannot replace integrated ore-specific pilot and operational evidence. The extent of independently audited mineral-ore applications in the wider literature cannot be determined from the supplied bibliography alone. Industrial decisions therefore require representative testwork, reconciled operating boundaries, credible uncertainty ranges, and alternatives compared on an equivalent feed-to-saleable-product basis.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

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